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BURN-OUT HEAT FLUXES UNDER FORCED WATER FLOW

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At present there is a considerable number of scientific works devoted to the investigation of boiling burn-out under forced flow of subcooled water and steam-water mixture in round tubes and partially in channels of different geometry.

However, the examination of all these works does not allow to make up a clear view of principal regularities the boiling burn-out is subjected to.

The systematization of available results is difficult because of the investigations carried on under forced water flow in tubes in spite of a great number of works do not involve the behaviour parameters in a wide range of their combinations. Therefore it is impossible to observe the variation of each parameter influence on burn-out heat flux $q_{b.a}$ with the variation of other parameters. There are few experimental works carried on the channels of geometry different from the tube geometry.

This report is devoted to the examination of experimental data on boiling burn-out under subcooled water and steam-water mixture flow in tubes in comparison with the data obtained for external flow around of a single tube in a symmetric annular gap, the tube placed along the axis of a square channel and external longitudinal flow over the rod bundles.

Analysis of the experimental data is based on the results of many years systematic investigations carried on by the authors of this report. Installations and methods of these experiments are not differed from the conventional

ones and not described there. The description of these installations was presented for example in [I,2,3].

BOILING BURN-OUT IN TUBES

I. Principal regularities

Results mentioned below were partially used in papers published earlier [I,4,6]. However, for the present report these results are made more accurate, supplied with new data and extended by parameters. A problem of principal regularities the boiling burn-out is subjected to is more important and interesting one. Virtually, this problem is reduced to the investigation of fixed parameter influence (pressure, flow rate and enthalpy of fluid in burn-out region) on $q_{б.о.}$

Curve dependences of burn-out heat flux upon mass water flow rate W_g with its parameters on saturation line in burn-out region are presented in Fig.I.

Deviations from the parameters corresponding to saturation line are no more in some experiments than I+I.5 grade aside of subcooling and 0.5 weight per cent aside of steam content(by heat balance calculation).

Analysis of curves according to the pressures* shows that $q_{б.о.}$ is in inverse dependence on pressure througout the interval, moreover, with the increase of mass water flow rate the dependence on pressure is decreased. The plots also show that flow rate influence on $q_{б.о.}$ is ambiguous and depends on pressure and rate itself.

Water enthalpy influence on $q_{б.о}$ is plotted in Fig.2. From these curves it may be seen that the value of $q_{б.о.}$ is in inverse dependence on enthalpy of water (in burn-out region) and, moreover, the water enthalpy influence is increased with the growth of water flow rate.

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* Absolute pressure is indicated everywhere.

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At the same relative enthalpy the character of curves changes with the variation of pressure and at constant pressure the character of curves depends on enthalpy of water. Ambiguity of water flow rate ifluence on $q_{b.o.}$ at pressures of I96 and 392 n/cm^2 appears in subcooled water region.

Thus, the ambiguous water flow rate influence on $q_{b.o.}$ firstly discovered by the authors of this report in I956(5) for the steam-water mixture region reveals in a more wide range of parameters

Resuming the curve dependences it may be drawn the following conclusion: degree of each behaviour parameter influence depends on its combination with other parameters. Thus, for example, water flow rate influence on $q_{b.o.}$ depends upon the fixed pressure and enthalpy values.

2. Additional factor influence

It is of interest the additional factor influence, viz: heating length, tube diameter and heat flux concentration non-uniformity over internal tube surface.

Experimental data illustrating in this report the principal boiling burn-out regularities are obtained on 8-9 mm inner diameter tubes and of I00 to 2I00 heating length.

The examination of experimental results in comparison with the data presented by the other authors shows that the tube length influence on $q_{b.o.}$ within the limits indicated does not appear in subcooled water region, but in the steam-water region at $\ell \geq$ 200 mm . It is necessary to note that up to now it is meant experimental results obtained at experimental set-up in a circulation loop of which the water flow pulsations occuring in a presence of pulse generator are absent (condenser etc.). However, a strong heating length influence on $q_{b.o.}$ in the presence of pulsations in the loop is mentioned earlier in the work [7] . Under these conditions $q_{b.o.}$ is in inverse proportionality to hea-

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ting tube length. In some cases this influence is evaluated by some hundred per cent.

It was observed by the authors (I) that in the subcooled water region for I373÷I962 n/cm^2 pressure range the internal tube diameter (d_{in} =4÷I2 mm) does not influence on $q_{b.o.}$. The latter is confirmed by experiments carried on by Ornatsky(8) on subcooled water at P =245 n/cm^2 showing the substantial increase of $q_{b.o.}$ in a case of decrease of d_{in} from 4 to I mm and the lack of influence in the range of d_{in} =4÷6 mm.

However, in the experiments carried on by Doroshuk Lantsman(9) at P =490÷I665 n/cm^2 it was observed the d_{in} influence on $q_{b.o.}$ in a whole range of d_{in}=3÷8mm, both in the subcooled water region and some more in steam-water region.

A strong d_{in} influence on $q_{b.o.}$ have been observed by Ribin(IO) for steam-water mixture at P =98I n/cm^2, $W_g=(3\div 20)\cdot 10^6 kg/m^2/hr$; x up to 0.35 in a range of d_{in} = =2÷IO mm .

The experiments carried on by the authors of this report confirmed the existence of d_{in} influence on $q_{b.o.}$ in steam-water mixture at P =98I and I373 n/cm^2 , W_g = =6.IO^6 and IO.IO^6 $kg/m^2/hr$, x = 0÷0.40 in the region of d_{in} =4.8÷I2 mm .

However, d_{in} influence problem on $q_{b.o}$ requires an additional detailed study.

It is of importance and interest the investigation of heat flux surface concentration non-uniformity influence on boiling- burn-out. The heat flux concentration non-uniformity in fuel elements of nuclear reactor core may occur in two cases, at least:

a) in a case of fissionable material concentration non-uniformity over a fuel element volume,
b) in a case of fuel element complex configuration with

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ribs filled with active material as a whole body of fuel element. As a rule, these ribs are firnished with curvatures in points of conjunction with fuel: element body in which arise the heat flux concentrations.

If the degree of heat flux concentration non-uniformity on a heat transfer surface is evaluated by the ratio of $q_{b.o}^{max}/q_{b.o.}^{aver}$, where $q_{b.o.}^{aver}$ is the average burn-out heat flux all over heat transfer surface and $q_{b.o.}^{max}$ is the maximum local burn-out heat flux, then in the first case this ratio may be not great and scarcely exceeds I.2 with regard for heat spreading and in the second case this ratio depends on curvature radius between the fuel element body and its rib and may achieve 2+3. In the latter case in the presence of ribs the water flow hydrodynamics may influence on $q_{b.o.}$

The experiments on the investigation of heat flux concentration non-uniformity influence on $q_{b.o.}$ carried out with round tubes of d_{in} =IO mm , tube length is 400 mm and with the eccentricity between external surfaces and internal ones (three values).

For these eccentricity values the ratio of $q_{b.o}^{max}/q_{b.o.}^{aver}$ determined according to the heat flux curves * is I.I2; I.28; I.50 .

Experimental results representing the heat flux concentration non-uniformity influence on $q_{b.o.}$ in comparison with the experiments carried on tubes heated uniformly are shown in Fig.3 .

From the plot it is seen if $q_{b.o}^{max}/q_{b.o.}^{aver}$ is more, then average burn-out heat flux is less. Thus according to the experimental results presented in Fig.3 the local maximum burn-out heat flux is approximately equal to $q_{b.o.}$ in the great subcooling range for tube heated uniformly, while with subcooling decrease and transition to steam-water mixture $q_{b.o.}^{max}$

* Heat flux curves are plotted according to the results of calculation by numerical method with regard for heat spread

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becomes greater than $q_{b.o}$ for tube heated uniformly. Moreover the concentration influence depends on behaviour water flow parameters, viz: in the subcooled water region the influence is more while in steam-water region the influence is less. The heat flux concentration non-uniformity influence falls with pressure increase as well as with the water flow rate growth. It is necessary to note that the experiments carried out in subcooled water and steam-water regions at pressures of 255, 98I and I765,8 n/cm^2 (II) showed that $q_{b.o}^{aver}$ is approximately equal for tube heated uniformly at $q_{b.o.}^{max}/q_{b.o.}^{aver}$ =I.8 .

If the heat flux concentration non-uniformity over heat transfer surface is due to the active material concentration non-uniformity over fuel element volume ("hot sports"), then having available the values of $q_{b.o.}^{max}/q_{b.o.}^{aver}$ one may neglect the influence of this factor taking into account that the maximum operating heat flux within a reactor is chosen, as a rule, with a margin relative to $q_{b.o.}$ not less than 2. Only in the case of $q_{b.o}^{max}/q_{b.o}^{aver} > $ I.2 (with curvatures at the rib base) it is necessary to take into account this factor.

Boiling burn-out at external longitudinal flow around the tubes

The authors of this report have carried on the boiling burn-out investigations at external water flow around a single tube in a symmetric annular gap. The experiments were carried on the heater-tube of d =I2 mm and annular gap width of I.5 mm; the heating length is 200 mm . The rate dependences $q_{b.o}=f(W_g)$ for pressure range 392–I962 n/cm^2 with water parameters over saturation line in a burn-out region is shown in Fig.4.

It is seen that the degree of water rate influence on burn-out heat fluxes is reversed from positive to zero (approximately). Rate dependences for subcooled water and

steam-water mixture at pressures of 392 and 784 and 98I n/cm^2 reveal the similar law (Fig.5).

The experimental results in terms of $q_{b.o.} = f(W_g)$ for a case of external flow around the tube placed along the square channel axis are presented in Fig.6 and for a case of external longitudinal flow around the tube bundles are shown in Fig.7.

From the comparison of rate dependences of $q_{b.o} = f(W_g)$ it follows that for such interval parameters where the flow rate influence on $q_{b.o.}$ is ambiguous for tubes with internal cooling the negative rate influence does not occur for tubes with external cooling.

From the point of published theories on boiling burn-out under forced fluid flow (I2-I4) the main difference in conformity with the law of flow rate influence on $q_{b.o.}$ for cases of internal and external tube cooling is not explained absolutely. Apparently, the most important features of burn-out phenomenon are not represented in the theoretical works cited.

There is another difference of boiling burn-out regularities at external and internal tube cooling. As it is mentioned above, the heating length at internal cooling does not influence on $q_{b.o.}$ for $\ell \gtrsim$ 200 mm and d_{in} =8-9 mm, at least. However, the experiments at external single tube cooling in annular gap showed a quite distinct influence of channel length (Fig.8).

The authors have carried on the investigation on burn-out heat fluxes with heat transfer on both surfaces of annular channel. As a rule, burn-out conditions are created on one heat transfer surface while from the other heating surface the additional heat flux of a certain quantity is supplied. In some experiments the boiling burn-out is observed on both surfaces simultaneously. It is established that at the pressures of 98I+I472 n/cm^2 and parameters fixed at the channel output the burn out heat fluxes

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in annular channel with double -sided heat supply are higher than in a caseof one-sided heating, hence the burn out heat fluxes on one heat transfer surface grow with the increase of additional heat flux on the other surface. This may be explained by the fact that under the identical conditions at channel output a partial coolant enthalpy influencing on burn-out rise moment on one heat transfer surface is less than the average one at the channel output because of additional heat supply from the other surface.

Enthalpy in a burn-out region may be determined from heat balance equation for annular channel by subtraction of enthalpy gain because of additional heat supply from the total enthalpy gain at the output. In this case the comparison of experimental results for annular channels with one-sided and double-sided heat supply leads to the results agreed.

CALCULATION RECOMENDATIONS

I. Subcooled water in tubes

The authors of many papers published proposed the calculation recommendations for the estimation of $q_{b.o.}$ under subcooled water. These recommendations have been obtained on the basis of separate experimental result treatment from the paper published. Therefore, the detailed analysis of particular dependences have not been perfomed but such one is an indispensable condition of reliability of calculation recommendations. Therefore, it was impossible to take account of rate influence ambiguity in a case of evaluation of water flow rate influence on $q_{b.o.}$. The rate influence is evaluated by variable but positive index.

The comparison of these calculation recommendations with experimental results in a wide range of parameters had revealed their full inapplicability in those parameter combinations where the water flow rate influence on $q_{b.o}$ is negative. In the work (5) an ambiguous water rate in-

fluence on $q_{б.о.}$ have been taken into account by the use of a variable index to be a function of pressure and enthalpy of water in a burn-out region. For $q_{б.о.}$ calculation the authors recommend one of the modifications of this equation.

$$K = K_d^{0,65}(110-240K_2)[1+0,75\cdot10^5/(7,4\cdot10^3 W)^{1,1+2K_1-0,3K_2}]\cdot10^{-5}$$

where $K = \frac{q_{б.о}}{r}\sqrt{\frac{\nu}{\sigma W_g}}$; $K_1 = \frac{\gamma''}{\gamma'}$; $K_2 = \frac{\Delta i}{r}$.

Application range of the equation:

$P = 294 \div 2060\, n/cm^2$

$W_g = 1 \div 15\, m/sec$

$\Delta t = 2 \div 200$ grad.

$d_{in} = 8 \div 10$ mm.

$\ell \geq 100$ mm

2. Steam-water mixture in tubes

It is proposed the following empirical formula for the $q_{б.о.}$ calculation under forced steam-water flow in tubes with regard of the tube interval diameter influence

$$q_{б.о} = 46,5\, W_g^{\,n}(1-x)^m\left(\frac{\gamma'}{\gamma''}\right)^{2,2}\left(1+\frac{8\cdot10^9}{W_g^{\,K}}\right)\cdot\frac{2,71}{d_{in}^{0,48}}\ \frac{вт}{m^2}$$

where

$n = 0,56 - 0,0189\frac{\gamma'}{\gamma''}$;

$m = 0,7\frac{\gamma'}{\gamma''} - 0,40$;

$K = 1,13 + 3,6\frac{\gamma''}{\gamma'} - 0,45x$

Application range of the formula:

$P = 981 \div 1962\, n/cm^2$;

$W_g = (4 \div 18)\cdot10^6\, kg/m^2/hr$;

$x = 0 \div 0,4$;

$d_{in} = 4 \div 12$ mm;

$\ell \geq 200$ mm

Recently the authors have obtained the following empirical formula for the pressures not so high.

$$q_{б.о} = [1,46\cdot10^{-4}\, r^{1,72}(1-x)^m - 0,116\, W_g]\frac{2,71}{d_{in}^{0,48}}\ \frac{вт}{m^2}$$

where

$m = 3,48 - 0,54\,(r/4,18\cdot10^6)$

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Application range of the formula:

$$p = 392 \div 981 \ n/cm^2;$$
$$W\gamma = (2 \div 18) \cdot 10^6 \ kg/m^2/hr;$$
$$x = 0 \div 0{,}40;$$
$$d_{in} = 4 \div 12 \ mm;$$
$$\ell \geq 200 \ mm.$$

3. External flow around a single tube in a symmetric annular gap

At present there are not enough of experimental data on $q_{б.о.}$ for annular gaps particularly on the investigation of additional factor influence (heating length, tube diameter, annular gap width) therefore it is not yet time to try to propose the calculation recommendations for a wide range of parameters with regard of additional factor influence. By virtue of this fact, only an empirical formula for the calculation of $q_{б.о.}$ for water with parameters on saturation line is represented below

$$q_{б.о} = 5{,}14 \cdot 10^{-3} \, r \, \gamma' \, \frac{W}{0{,}25 + W} \quad \frac{бm}{m^2}$$

Application range of the formula:

$$p = 392 \div 1962 \ n/cm^2;$$
$$W = 2 \div 7 \ m/sec;$$
$$\ell = 200 \ mm.$$

Annular gap width is I.5 mm and heater tube diameter is I2 mm .

NOTATION

$q_{б.о}$ MWt/m^2 - burn-out heat flux;
p n/cm^2 - absolute pressure;
$W\gamma$ $kg/m^2/hr$ - mass water flow rate;
W m/sec - linear water rate in burn-out region;
γ' kg/m^3 - water density on saturation line;
γ'' kg/m^3 - steam density on saturation line;

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r j/kg - latent heat of water evaporation;

σ n/m - surface feusion coefficient of steam-water boundary

ν m^2/hr - water kinematic viscosity coefficient on saturation line

$\Delta t_{sub\,grad.}$ - water subcooling up to saturation temperature in burn-out region;

$\frac{\Delta i}{r}$ - relative enthalpy (negative for subcooled water and positive for steam-water mixture; in the latter case it equals weight steam content in unit fractions).

Δi j/kg - heat of subcooling for subcooled water (negative) or heat of overheating for steam-water mixture (positive).

d_{in} mm - internal tube diameter;

ℓ mm - heated length of experimental region.

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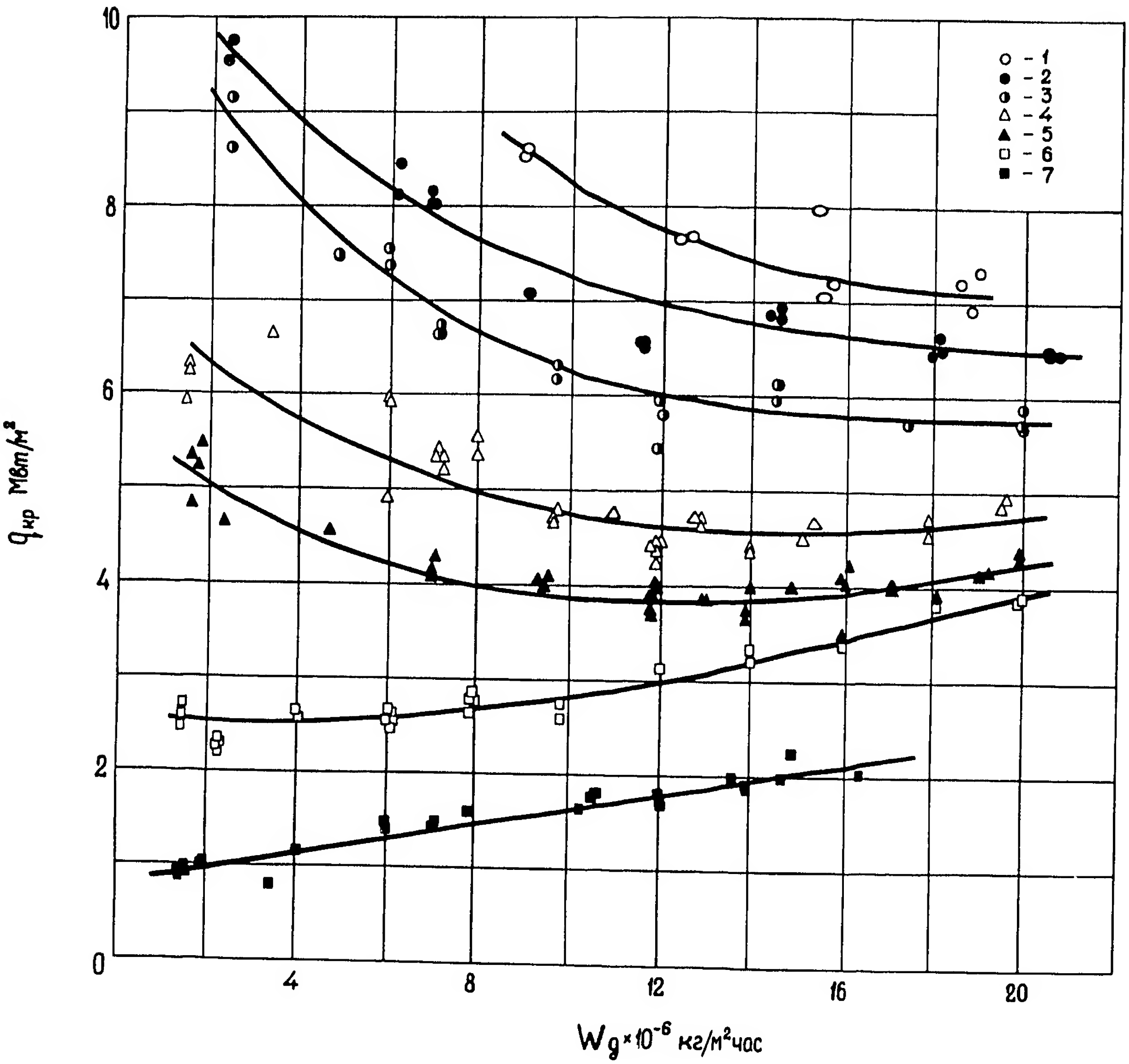

Fig.I. $q_{\ell.0}$ is on saturation line for tubes. I,2,3,4,5,6,7 correspond to pressures I96; 294; 392; 784; 98I; I373; I962 n/cm^2.

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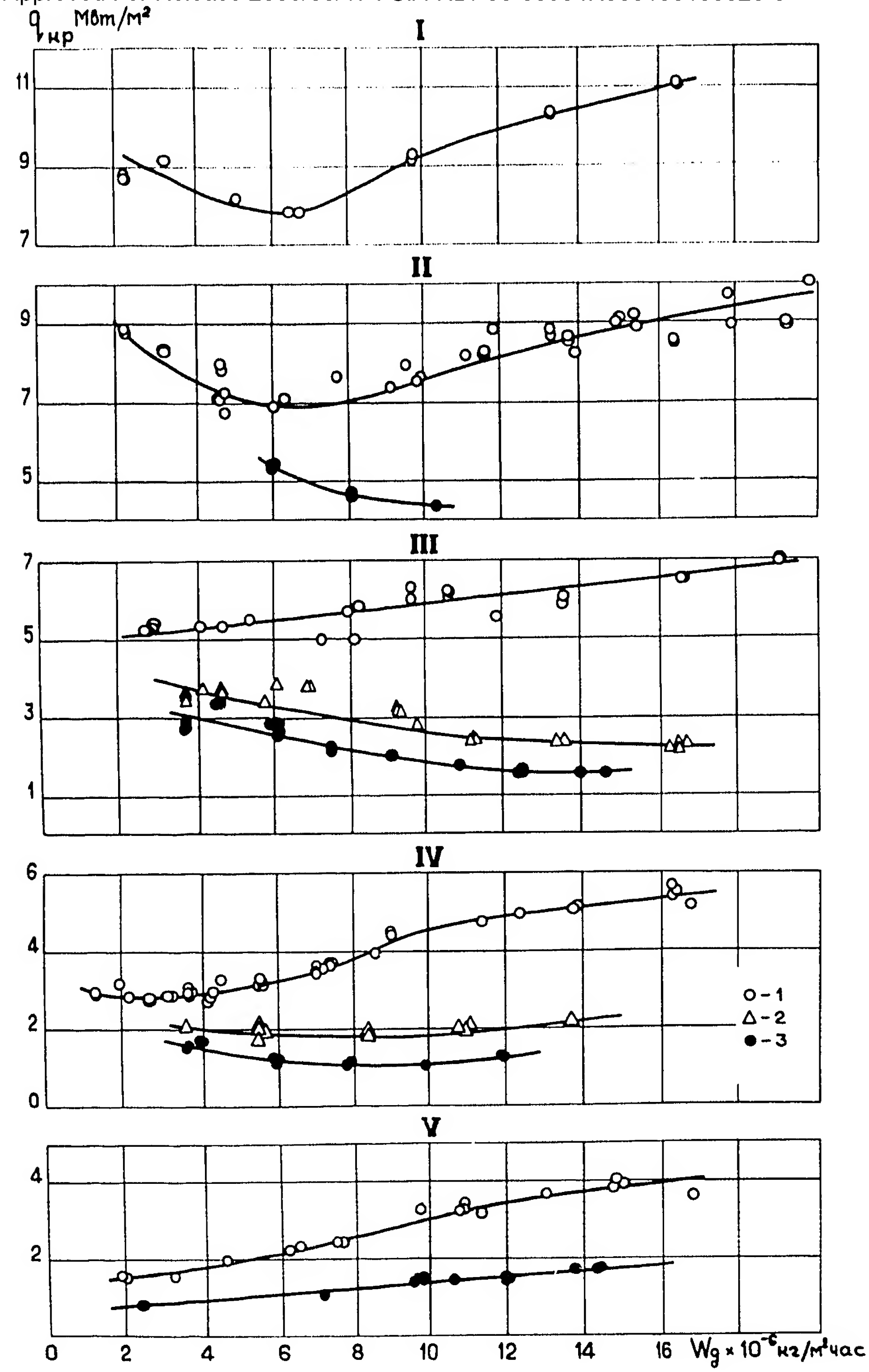

Fig.2. $q_{кр.о}$ is at different enthalpy for tubes. I,2,3 correspond to relative enthalpy- 0.I; 0.I; 0.2.

I,II,III,IV,V- correspond to pressures I96; 392; 98I; I373; I765.8 n/cm^2.

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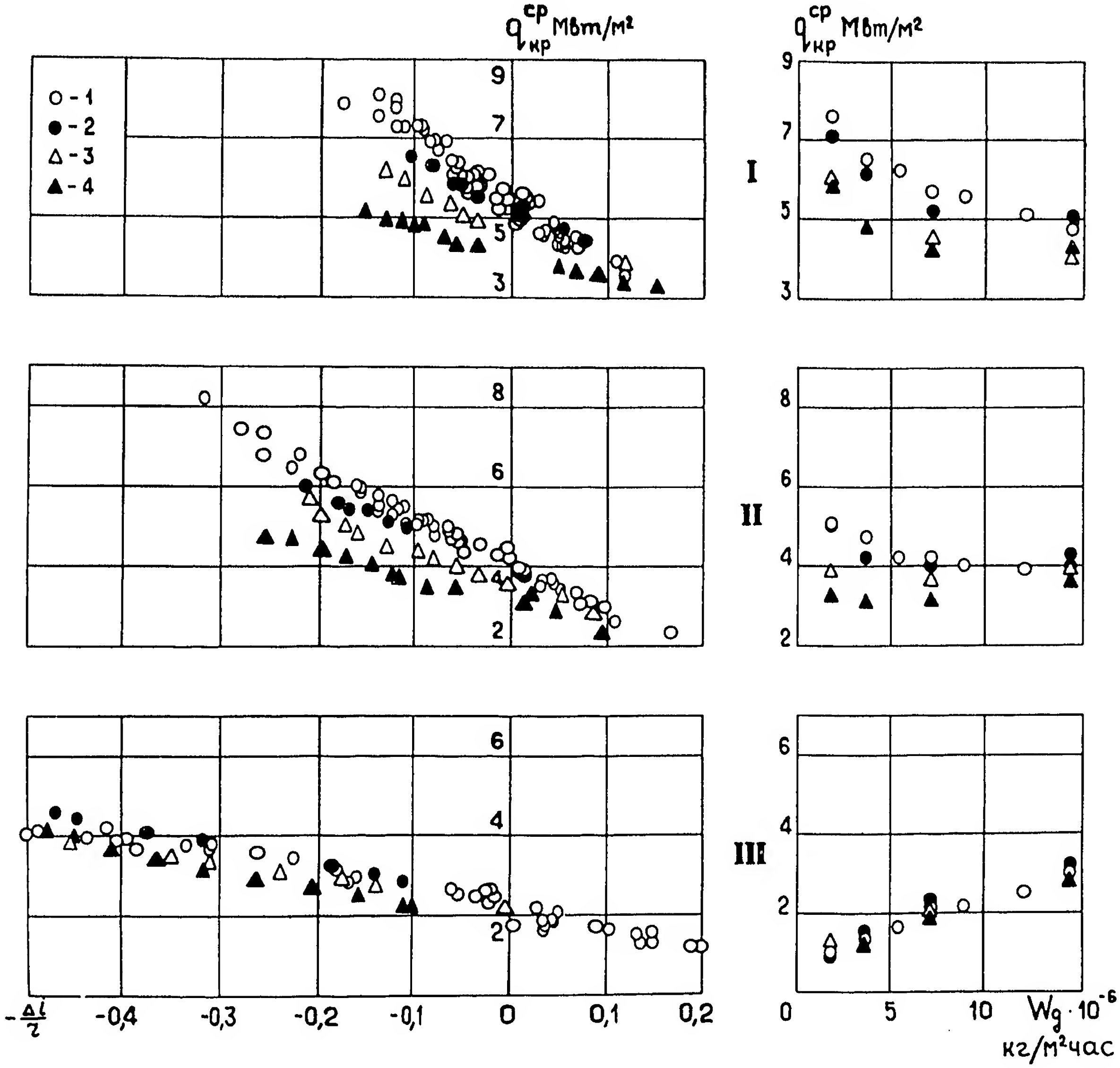

Fig.3. The heat flux concentration non-uniformity influence on $q_{6.0}$ in round tubes. I,2,3,4-correspond to values $q^{max}_{6.0}/q^{aver}_{6.0}$ of -I;I.I2;I.28;I.50. I,II,III,-correspond to pressures 588,98I,I765.8 n/cm^2. All $q_{6.0}=f(W_g)$ dependences are given for $\frac{\Delta i}{r}=0$, and $q_{6.0}=f(\frac{\Delta i}{r})$ for mass velocity $7.2.I0^6$ kg/m²/hr.

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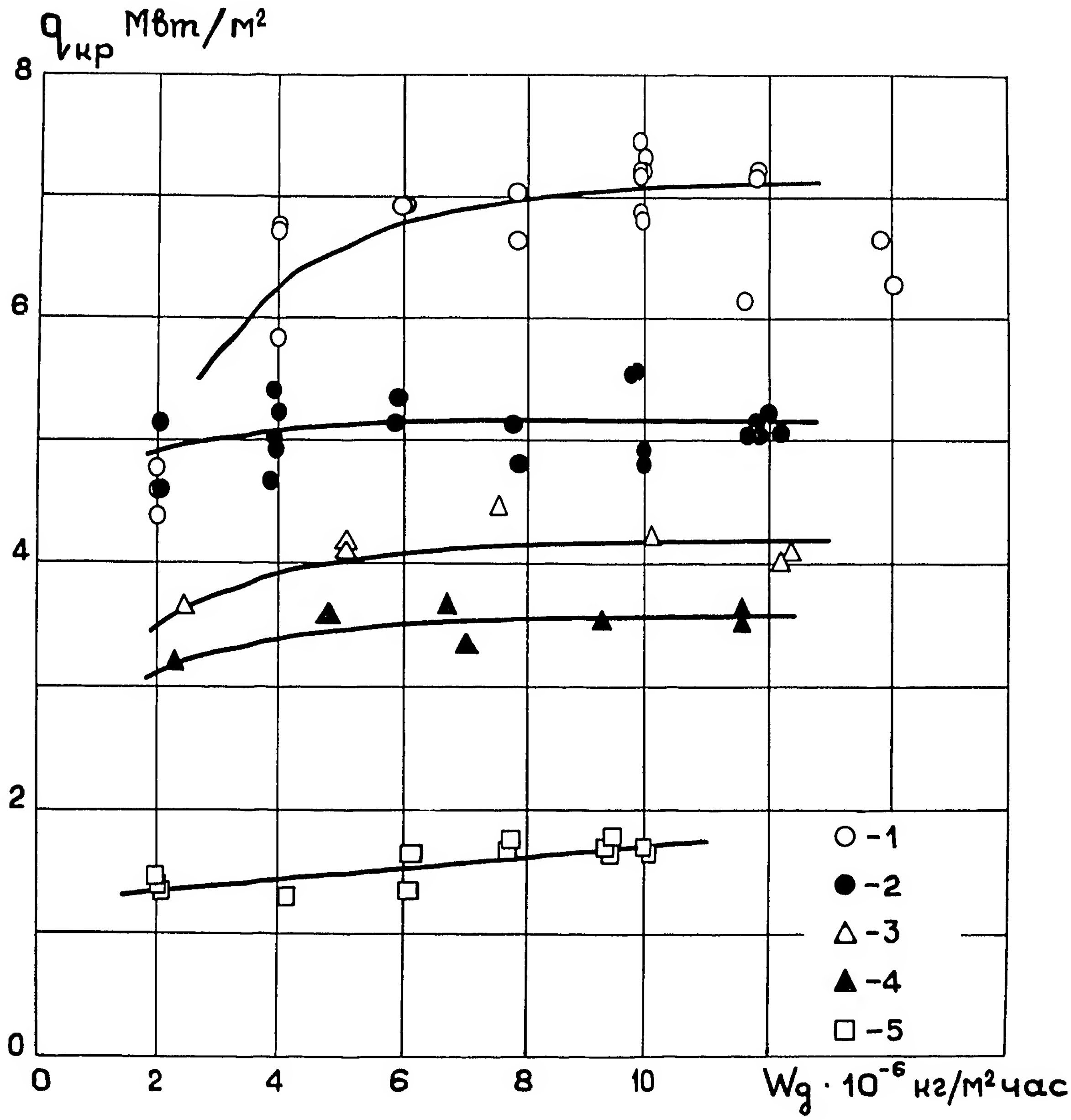

Fig.4. $q_{кр.о}$ is on saturation line for the annular gap.
I,2,3,4,5– correspond to pressures 392, 784, 98I, I274, I962 $н/см^2$.

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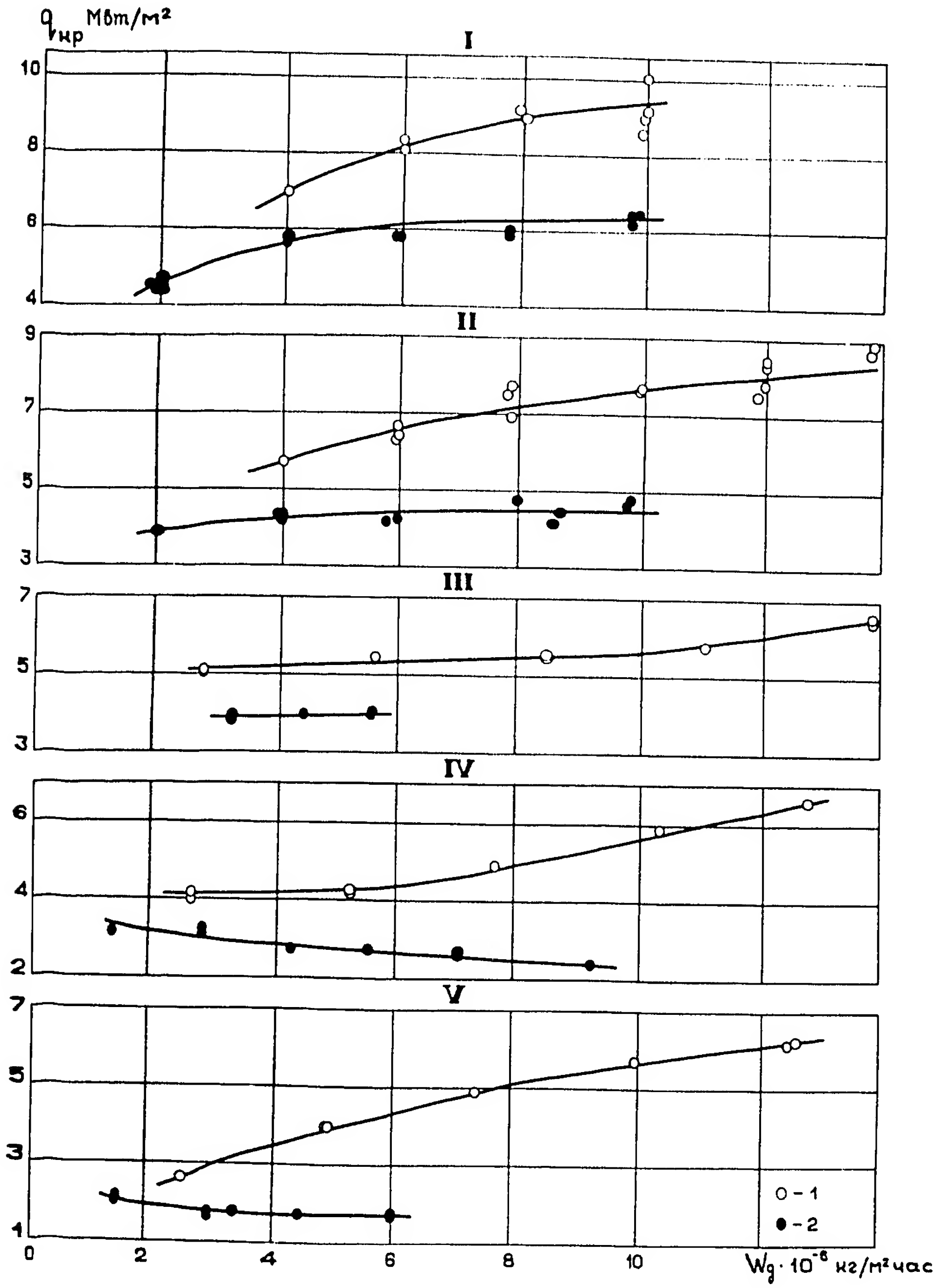

Fig.5. $q_{кр}$ is at different enthalpy for annular gap.
I-subcooling of 40 grade; 2- $\frac{\Delta i}{r}$ =0.I
I,II,III,IV,V-correspond to pressures 392; 784; 98I; I470; I765.8 n/cm^2.

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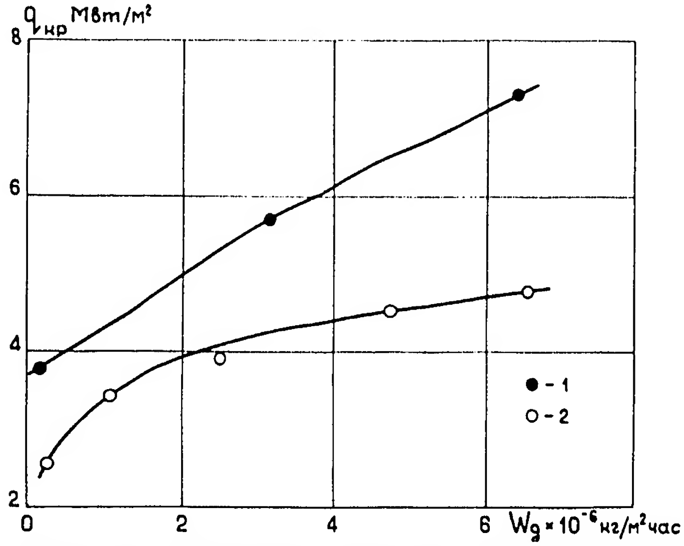

Fig.6. $q_{cr.o}$ is at external flowing around the tube placed along the square channel axis of dimensions I6.6xI6.6 mm, d_{ext} =I2 mm, ℓ = 200 mm, I – P=294 n/cm^2, Δt_{sub}=IOgrade, 2– P=98I n/cm^2, Δt_{sub}=5 grade

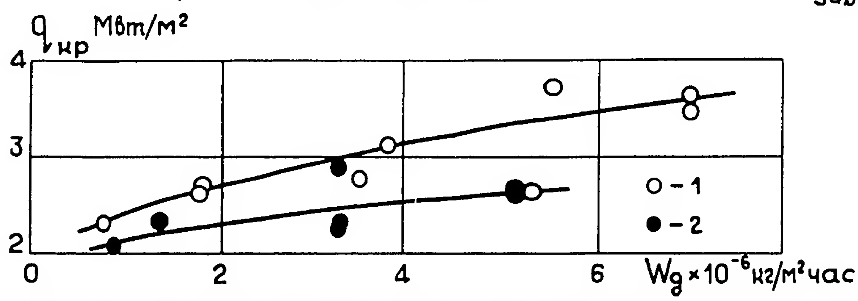

Fig.7. $q_{cr.o}$ is at longitudinal flow around the bundles consisting of 7 tubes of dimensions 5x0.25mm, Triangular lattice with a 6.5 mm spacing ; I-P=98I n/cm^2, $\frac{\Delta i}{r}$=0.I; 2-P=686 n/cm^2, $\frac{\Delta i}{r}$ =0.2.

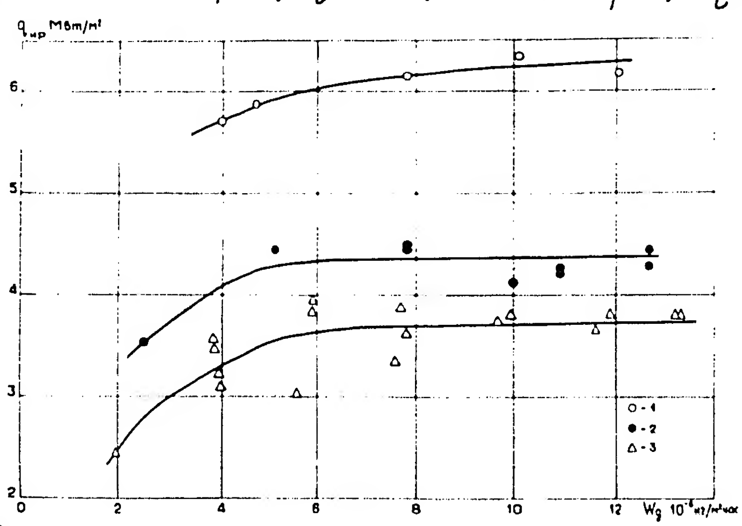

Fig.8. $q_{cr.o.}$ is on saturation line at external cooling of a single tube in annular gap for various heating length, P =98I n/cm^2; I,2,3 correspond to heating length of IOO, 200 and 400 mm .

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